Dark Sector Searches at Intensity Frontier Experiments*

Natalia Toro

Cross-Frontier Dark Sectors Meeting

July 16, 2021

*This is not a summary talk

Goals for This Talk

- "Why are Dark Sectors a compelling opportunity for the next decade?"

  And how to think about their scope

- "How do small and multi-purpose experiments across different experimental frontiers confront this landscape?"

Key stories for RF6 this Snowmass

- Bridging the GeV-to-TeV Gap

Valuable joint effort for RF6 and EF9,10

Perspective in this talk informed by past community & planning workshops and my own interests – Snowmass is just beginning!

What is a Dark Sector?

New physics neutral under Standard Model forces

- Dark matter seems a strong hint of a dark sector
- Natural framework for exploring new low-energy phenomena & anomalies

The Portals

Dark sector interactions with SM are restricted by SM gauge invariance

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

Illustrative example, simply compatible with predictive DM cosmology;

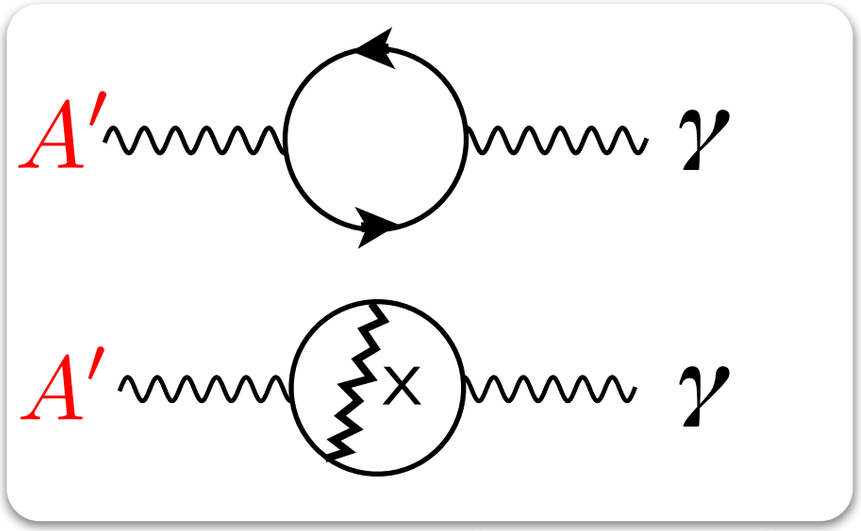
Dark photon and Higgs inherit SM flavor structure (Q_{EM} / $Y_{L,U,D}$), Axion and Neutrino portals have explicit flavor structure

How Dark Is It?

Origins of Small Couplings and Masses

Small couplings are **generic** if portal interactions generated radiatively

- Some portal interactions are further suppressed by small Yukawas



$$g_{\rm SM} \sim (10^{-6} - 10^{-2})e$$

Given small couplings, valuable to consider sub-weak-scale masses – comparable to electron and proton masses (and in some cases even lighter)

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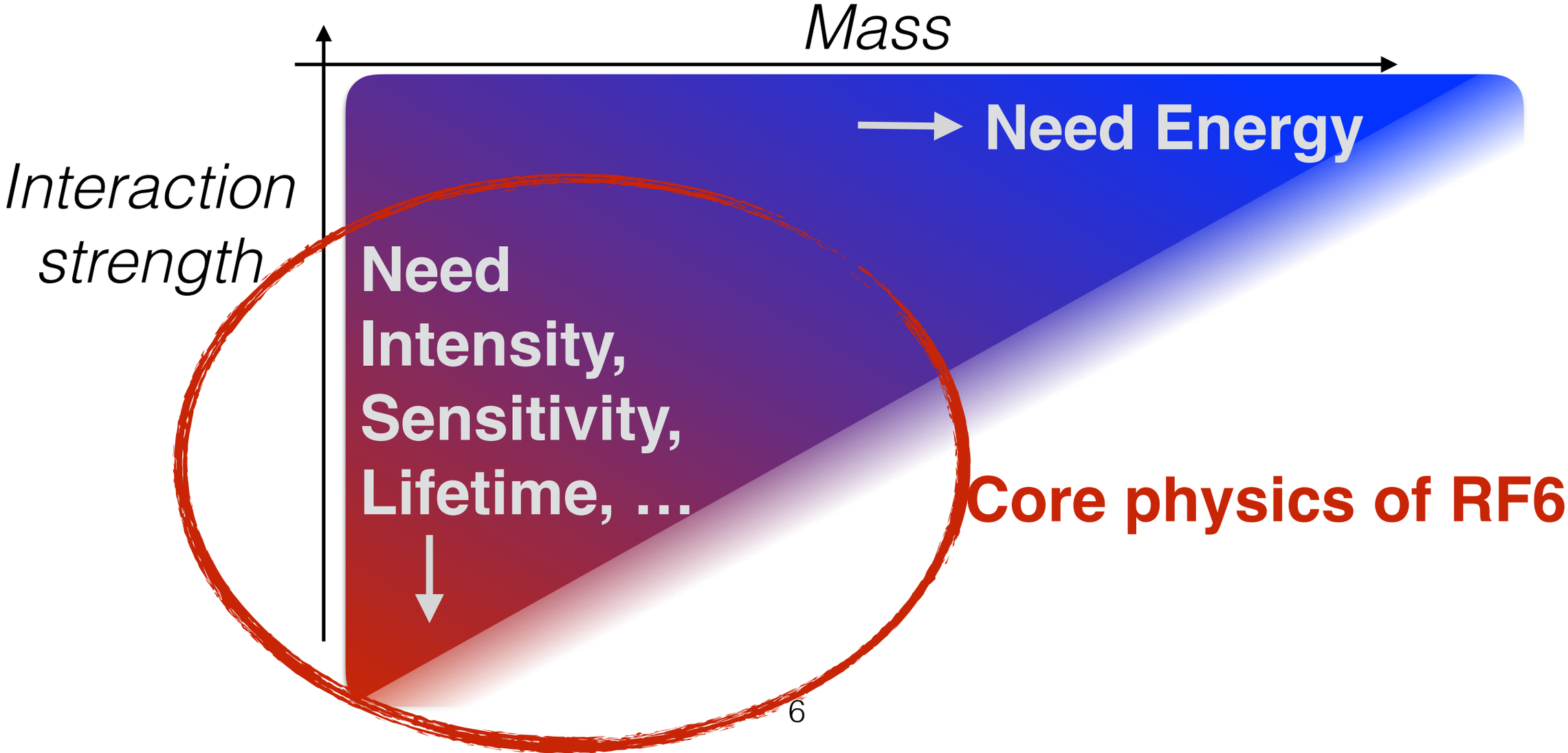
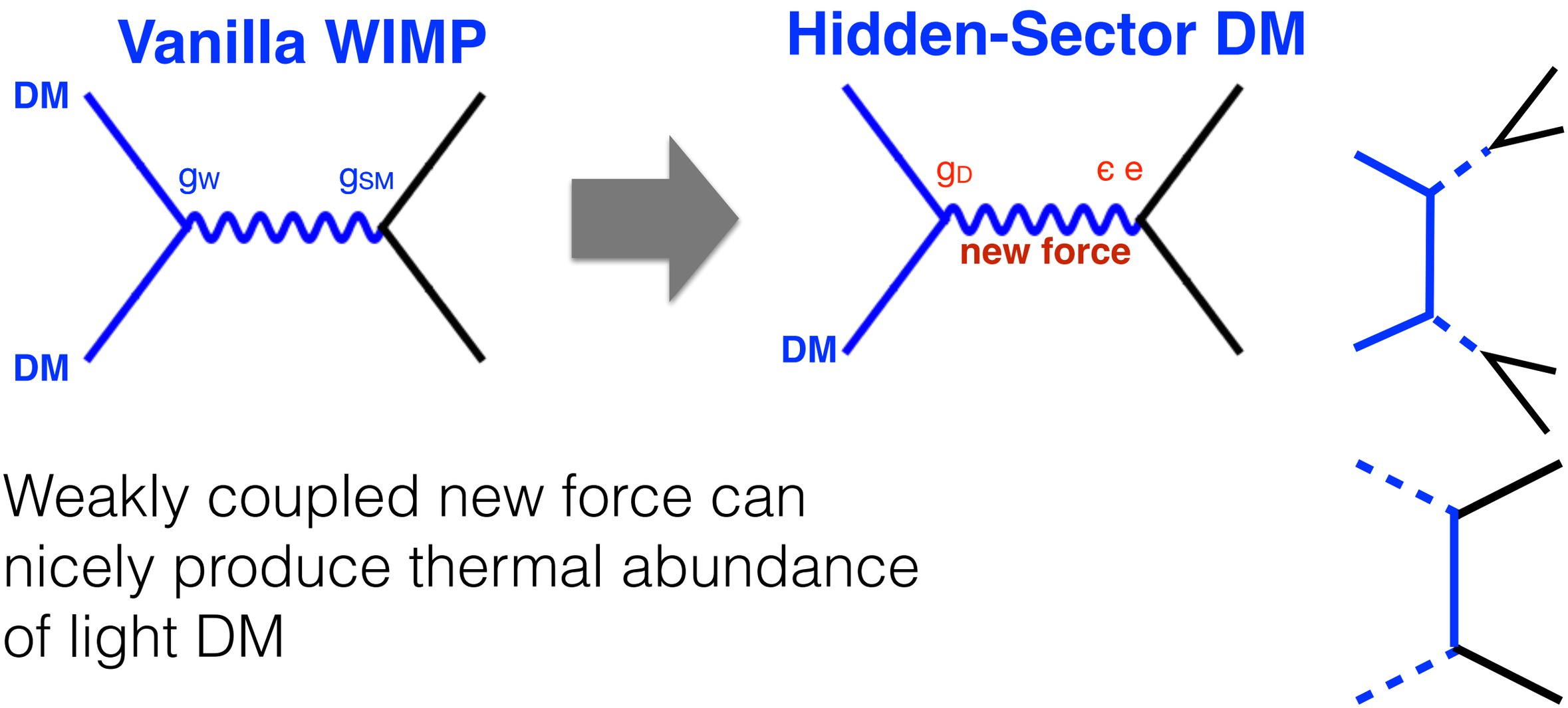


Dark Matter from a Dark Sector

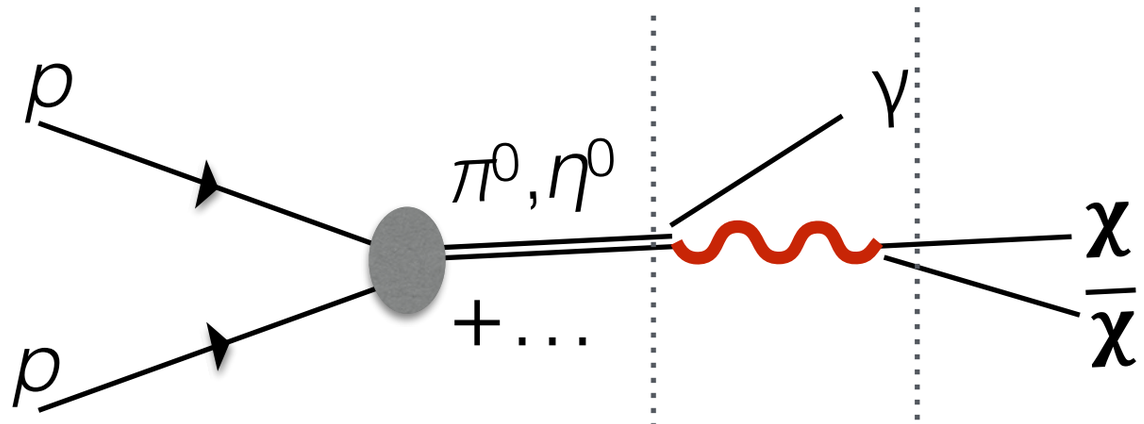
An example of a simple & exciting benchmark model



Weakly coupled new force can nicely produce thermal abundance of light DM

Force-carrier can have other interesting signals (both accelerator and cosmic)

Many Faces of Dark Sectors



People & facilities naturally organize by **initial-state**…

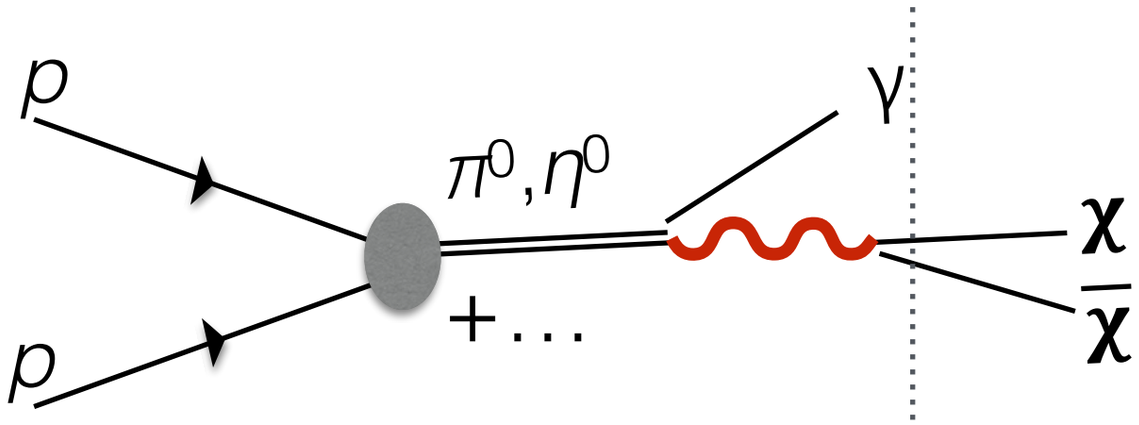
1. Theory of dark sectors
2. Dark sectors at electron-positron colliders
3. Dark sectors at fixed target / beam dump experiments (electron, positron, proton, and muon beams)
4. Dark sectors at kaon factories
5. Low-mass dark sectors at energy-frontier facilities (cross-group with EF09 - BSM: More general explorations / EF10 - BSM: Dark Matter at colliders)
6. Dark sectors at neutrino experiments (cross-group with NF03 - Neutrino physics - BSM)
7. Other experimental opportunities

x Theories naturally organize by **intermediate-state** "portals"

x Science case naturally aligned with whether **final-state** is SM, non-SM, or mixed

All three axes are important, both in mapping the physics and understanding detector design and capabilities.

The Final-State Axis



"Once you get in to the dark sector, what do you look for?"

non-SM

Dark Matter Production

Producing stable particles that could be (all or part of) the Dark Matter

SM

Portal-Mediator Decays to SM

Systematically explore the minimal couplings of SM to dark sectors

mixed

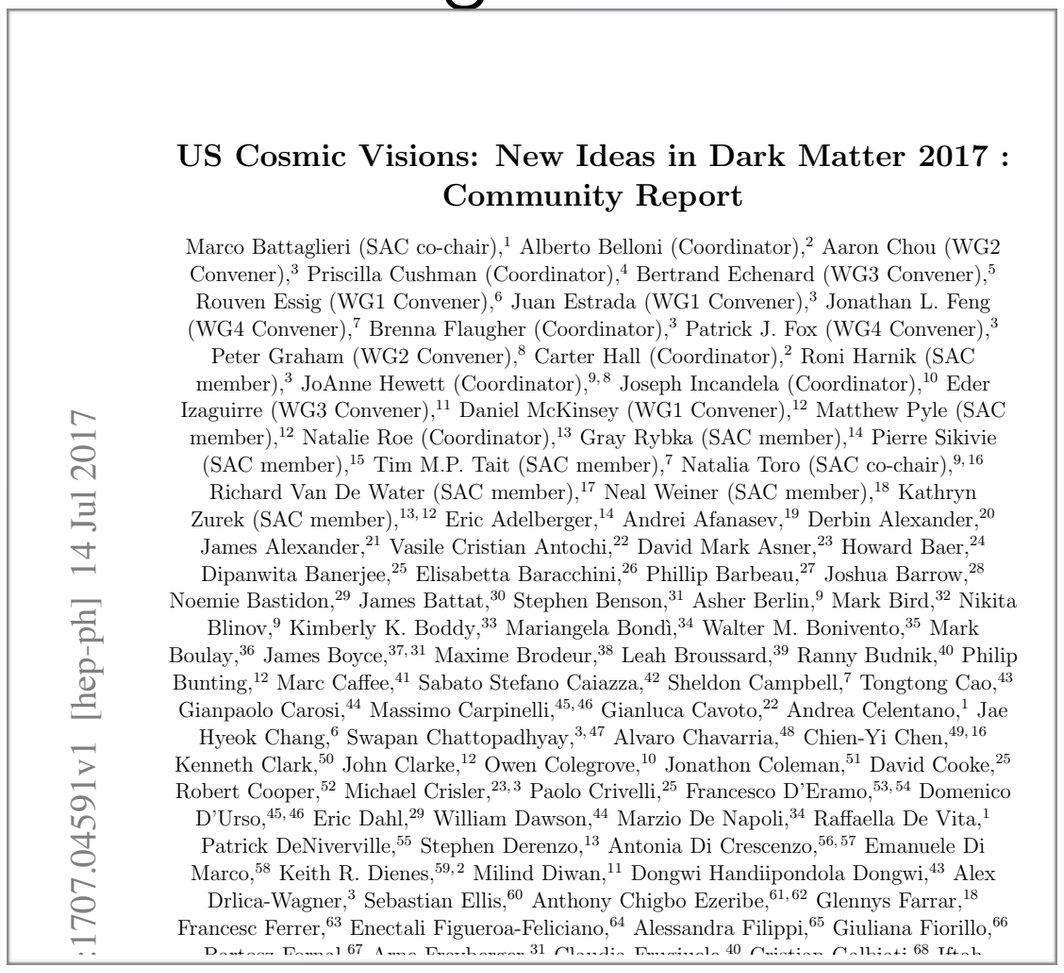
Structure of the Dark Sector

There could be a rich sector of new physics under our noses

These 3 possibilities are well aligned with what makes dark sectors viscerally exciting!

Dark Sectors <2020

- Many grassroots workshops since ~2009:
  - Dark Forces and Dark Sectors @ SLAC,
    Dark Interactions @ BNL, DM at Accelerators in Italy
- Significant momentum in last few years on community-wide planning in small experiments relevant to dark matter, including accelerator searches for dark sectors



US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng (WG4 Convener),[7] Brenna Flaugher (Coordinator),[3] Patrick J. Fox (WG4 Convener),[3] Peter Graham (WG2 Convener),[8] Carter Hall (Coordinator),[2] Roni Harnik (SAC member),[3] JoAnne Hewett (Coordinator),[9,8] Joseph Incandela (Coordinator),[10] Eder Izaguirre (WG3 Convener),[11] Daniel McKinsey (WG1 Convener),[12] Matthew Pyle (SAC member),[12] Natalie Roe (Coordinator),[13] Gray Rybka (SAC member),[14] Pierre Sikivie (SAC member),[15] Tim M.P. Tait (SAC member),[7] Natalia Toro (SAC co-chair),[9,16] Richard Van De Water (SAC member),[17] Neal Weiner (SAC member),[18] Kathryn Zurek (SAC member),[13,12] Eric Adelberger,[14] Andrei Afanasev,[19] Derbin Alexander,[20] James Alexander,[21] Vasile Cristian Antochi,[22] David Mark Asner,[23] Howard Baer,[24] Dipanwita Banerjee,[25] Elisabetta Baracchini,[26] Phillip Barbeau,[27] Joshua Barrow,[28] Noemie Bastidon,[29] James Battat,[30] Stephen Benson,[31] Asher Berlin,[9] Mark Bird,[32] Nikita Blinov,[9] Kimberly K. Boddy,[33] Mariangela Bondì,[34] Walter M. Bonivento,[35] Mark Boulay,[36] James Boyce,[37,31] Maxime Brodeur,[38] Leah Broussard,[39] Ranny Budnik,[40] Philip Bunting,[12] Marc Caffee,[41] Sabato Stefano Caiazza,[42] Sheldon Campbell,[7] Tongtong Cao,[43] Gianpaolo Carosi,[44] Massimo Carpinelli,[45,46] Gianluca Cavoto,[22] Andrea Celentano,[1] Jae Hyeok Chang,[6] Swapan Chattopadhyay,[3,47] Alvaro Chavarria,[48] Chien-Yi Chen,[49,16] Kenneth Clark,[50] John Clarke,[12] Owen Colegrove,[10] Jonathon Coleman,[51] David Cooke,[25] Robert Cooper,[52] Michael Crisler,[23,3] Paolo Crivelli,[25] Francesco D'Eramo,[53,54] Domenico D'Urso,[45,46] Eric Dahl,[29] William Dawson,[44] Marzio De Napoli,[34] Raffaella De Vita,[1] Patrick DeNiverville,[55] Stephen Derenzo,[13] Antonia Di Crescenzo,[56,57] Emanuele Di Marco,[58] Keith R. Dienes,[59,2] Milind Diwan,[11] Dongwi Handiipondola Dongwi,[43] Alex Drlica-Wagner,[3] Sebastian Ellis,[60] Anthony Chigbo Ezeribe,[61,62] Glennys Farrar,[18] Francesc Ferrer,[63] Enectali Figueroa-Feliciano,[64] Alessandra Filippi,[65] Giuliana Fiorillo,[66] Bartosz Fornal,[67] Anna Fratbergar,[31] Claudia Frugiuele,[40] Cristian Galbiati,[68] Iftah

Cosmic Visons community workshop 2017 (~mini-Snowmass)

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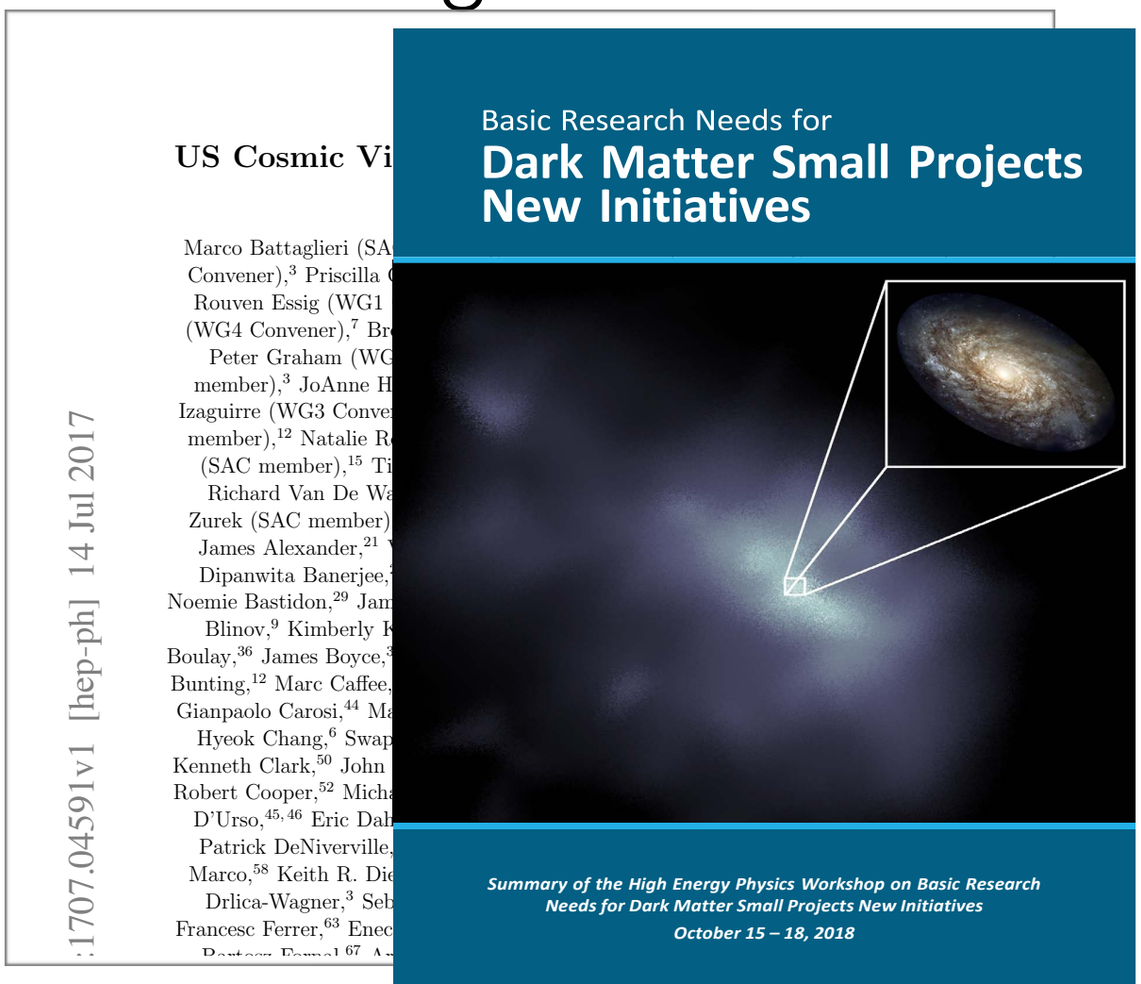


Cosmic Visons community workshop 2017 (~mini-Snowmass)

Basic Research Needs (BRN) workshop 2018: *non-FACA* panels charged by DOE with identifying priority **science** (not projects) in Dark Matter scope, achievable with small US-based experiments

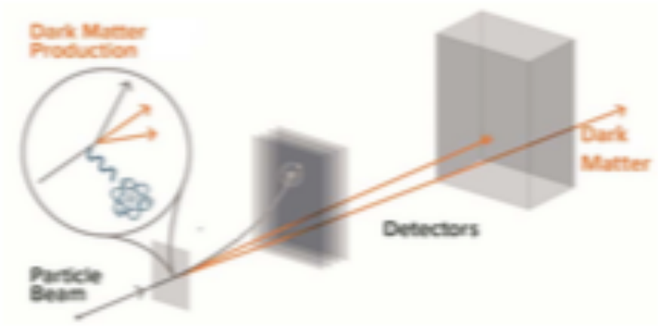
BRN Priority Research Directions

Summary of the High Energy Physics Workshop on Basic Research Needs for Dark Matter Small Projects New Initiatives

October 15 – 18, 2018

PRD 1

Create & Detect Dark-Matter Particles at Accelerators

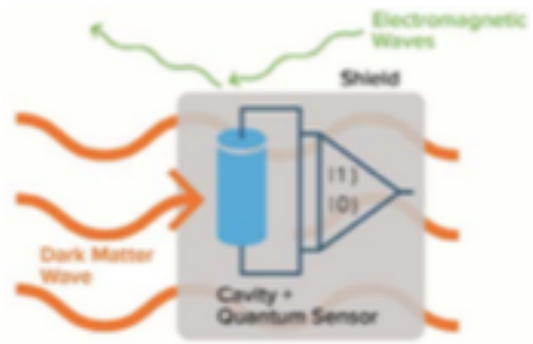


PRD 2

Detect Galactic Particle Dark Matter Underground

PRD 3

Detect Galactic Wave Dark Matter in the Laboratory



Success!

Experiments in all 3 PRDs received planning funds through 2019 FOA

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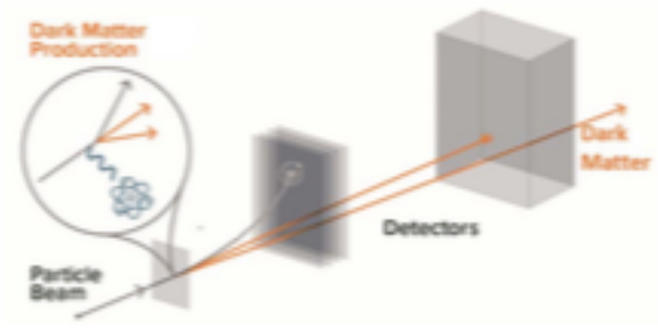

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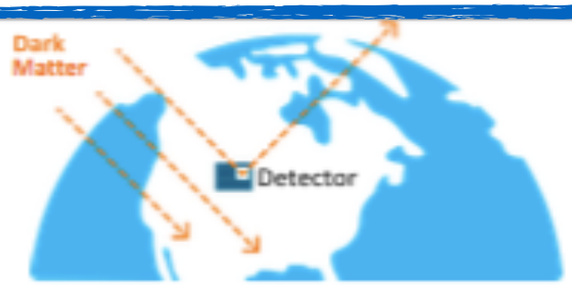

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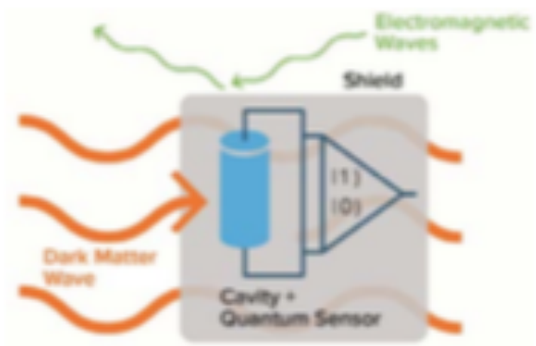

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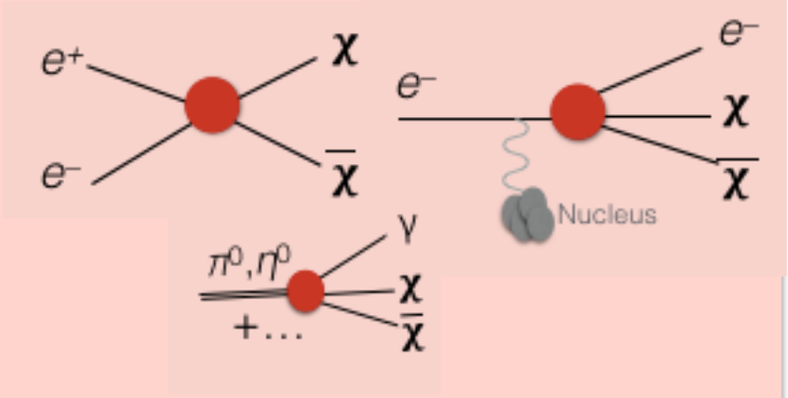
Thrust 1 (near term): Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.

Thrust 2 (near and long term): Explore the structure of the dark sector by producing and detecting unstable dark particles.

BRN and Final States

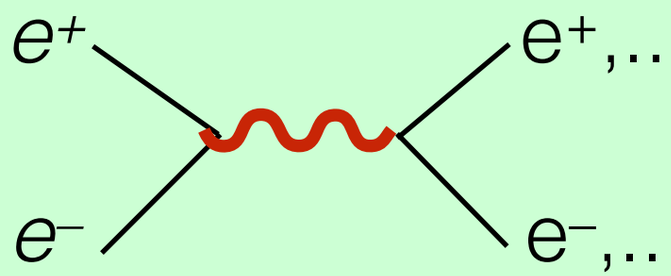
Dark Matter Production

BRN Thrust 1

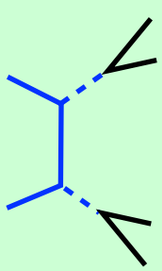


+Millicharges

Portal-Mediator Decays to SM

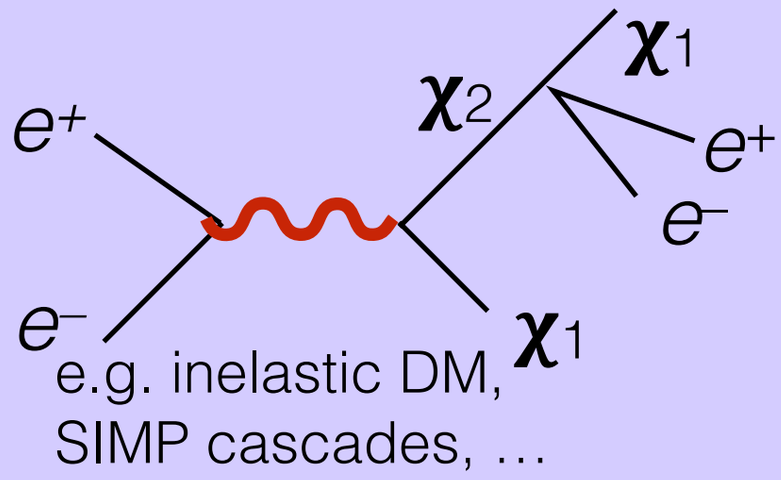


Scalars
(including secluded DM motivation),
ALPs, NHLs



Structure of the Dark Sector

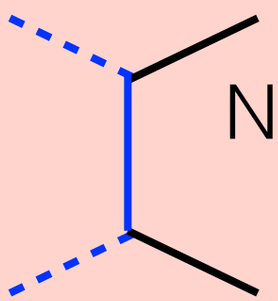
BRN Thrust 2



e.g. inelastic DM, SIMP cascades, …

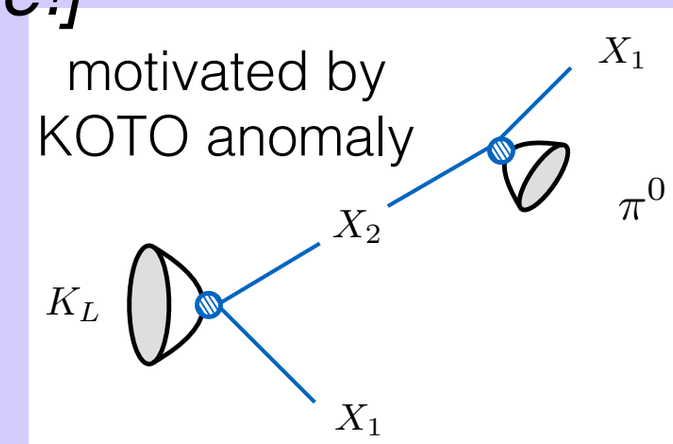
BRN report featured DM-motivated examples of each, emphasizing exciting near-term opportunities for dark photon portal

*Final-State organization also applies to other portals, facilities, and motivations [a few examples below, **far** from exhaustive!]*



Neutrino-portal thermal DM

motivated by KOTO anomaly



BRN → Snowmass

- PRD thrusts reflect the compromise between wanting to explore ***everything*** and needing to identify highlights if ***anything*** is going to get funded
- BRN charged to focus on small experiments and US facilities (and dark matter) – Snowmass RP6 **must** enlarge scope, **should** maintain BRN's momentum
  - Expanding list of "high-value" targets – finite, motivated, and accessible destinations in benchmark landscape – may be one way to do this.

Goals for This Talk

- "Why are Dark Sectors a compelling opportunity for the next decade?"

Key stories for RF6 this Snowmass

- "How do small and multi-purpose experiments across different experimental frontiers confront this landscape?"

- Bridging the GeV-to-TeV Gap

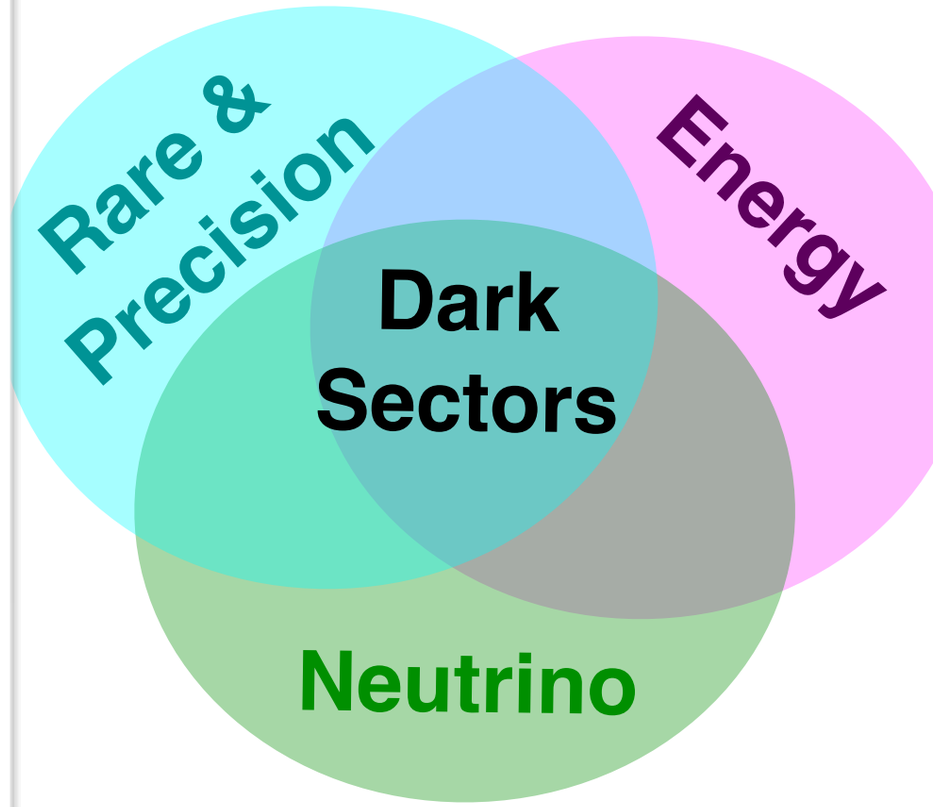
Valuable joint effort for RF6 and EF9,10

Perspective in this talk informed by past community & planning workshops and my own interests – Snowmass is just beginning!

Dark Sectors Are Everywhere

[table is probably incomplete]

	e/μ missing energy/ momentum	e± thin target	e±/μ beam dump	p far beam dump (incl. ν)	p near beam dump	Kaon factories	e+e− collider	EF Multi-Purpose Experiments	EF Dedicated Experiments
	NA64, LDMX, M3	HPS, APEX, DarkLight, PADME, μDM, BMN, MAGIE, JLab, BMAPS	BDX, BDX-DRIFT, DarkMESA, E137	Fermi, SUBMET, MiniBooNE-DM, COHERENT, BNB, LSND, DUNE	Dark**Quest, SHiP, CHARM...	NA62, KOTO, KLEVER...	Belle II, BES-3, BaBar, BaNe	ATLAS, CMS, LHCb	FASER, CODEX-b, milliQan, MATHUSLA
Low-Inv-Mass Dark Matter Production	✔		✔	✔✔		✔	✔		
Dark Photons and other Vectors→SM	✔	✔	✔		✔	✔	✔	✔	✔
Millicharges	✔			✔✔	✔				✔
Dark Scalars		✔			✔	✔	✔	✔	✔
ALPs		✔			✔	✔	✔	✔	✔
Neutral Heavy Leptons				✔	✔	✔		✔	✔
Semi-Visible & Cascades	✔	✔	✔	✔✔	✔	✔	✔	✔	✔



Takeaway: The physics doesn't align by facility/frontier*!

*except maybe Higgs portal λ coupling

RF6 seeks engagement from **everyone** studying this physics at ANY accelerator-based facility, and aims to build a comprehensive report. Please join us!

Liaisons are there to facilitate [not replace] involvement.

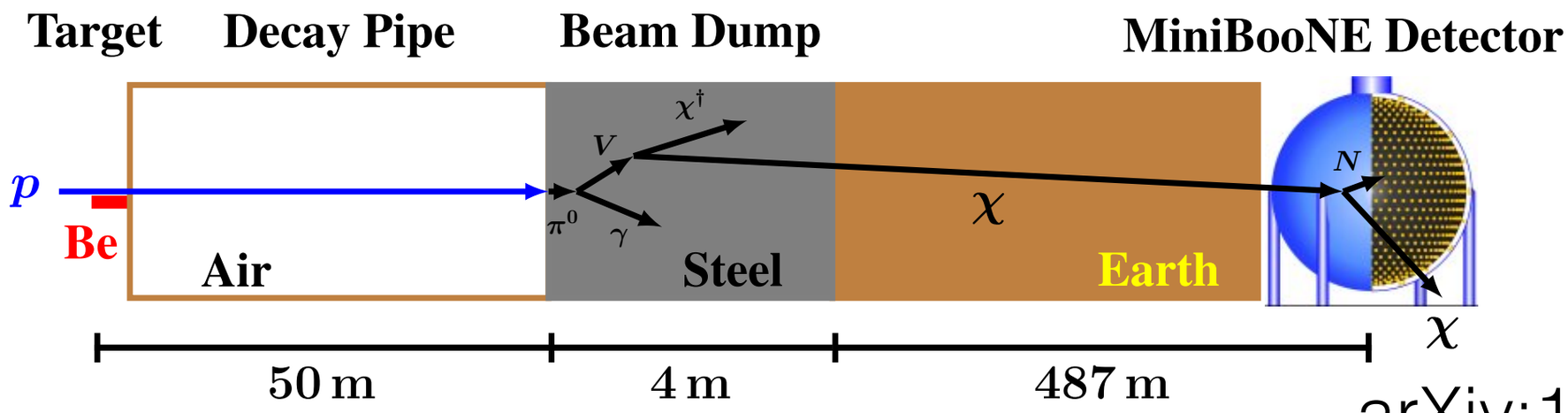
Why Intensity?

- Physics crosses frontiers, but also cares about details! **Low- and high-energy experiments,** as well as **small and multi-purpose experiments**, complement each other *because* they have different strengths.
  - Given structure of this meeting, I felt obliged to include a primer for LHC-based physicists on some of the things experiments at smaller and/or lower-energy facilities can do especially well.

    For simplicity I take most examples from dark matter; Maxim will emphasize flavor probes.

  - **This is only half the story.** And recent ideas for finding similar conditions, often with some advantages, in Energy Frontier environments are very exciting!

High Luminosities

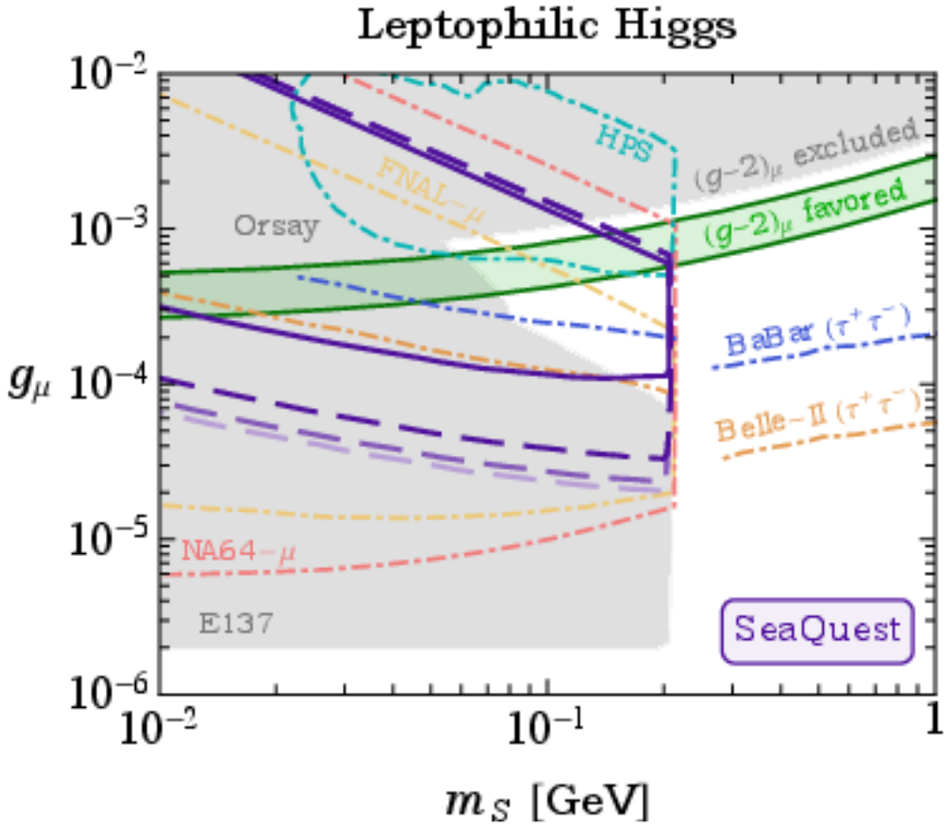


arXiv:1807.06137

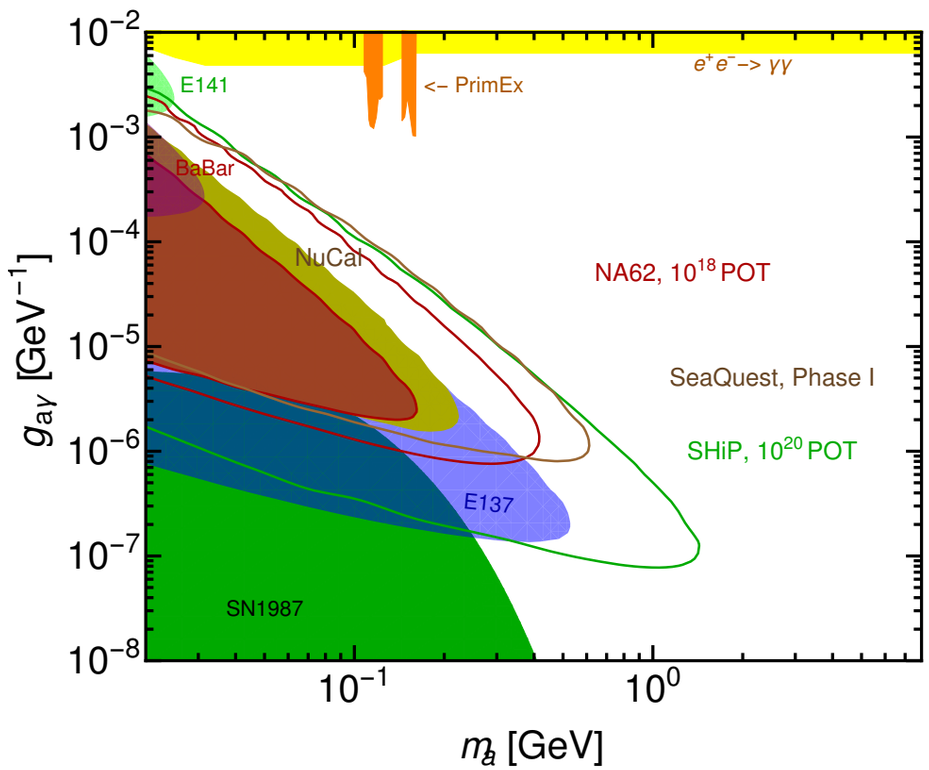
- e.g. 10^{20} (10^{23}) protons on target at MiniBooNE (COHERENT)
  - Typical proton travels 10s of cm through the dump → luminosities at the level of 10^{4}–10^{7} ab^{-1}
  - Similar story for electron beam dumps, w/ distinct shielding, background, detector size trade-offs
- This extreme luminosity allows searches for signals with inherently tiny efficiency like dark matter scattering in downstream detector.

Secondary Beams

Collimated showers of secondary particles can seed reactions for which primary beam particle has insufficient coupling



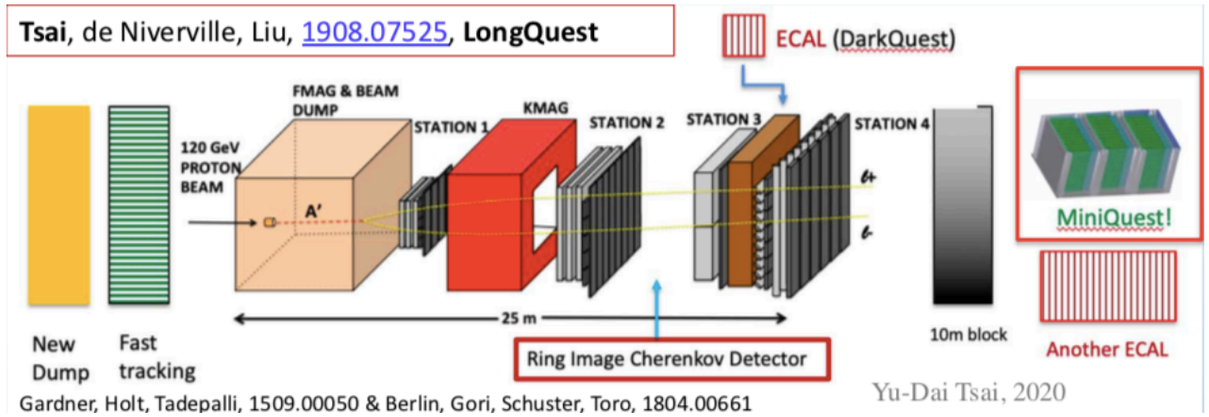
1804.00661 Berlin, Gori, Schuster, NT
leptophilic Higgs from secondary muons



1904.02091 Döbrich,Jaeckel, Spadaro
ALPs from secondary photons

Near, Forward Detectors

p beam: DarkQuest/LongQuest/SpinQuest



Excellent for low-mass displaced vtx sensitivity

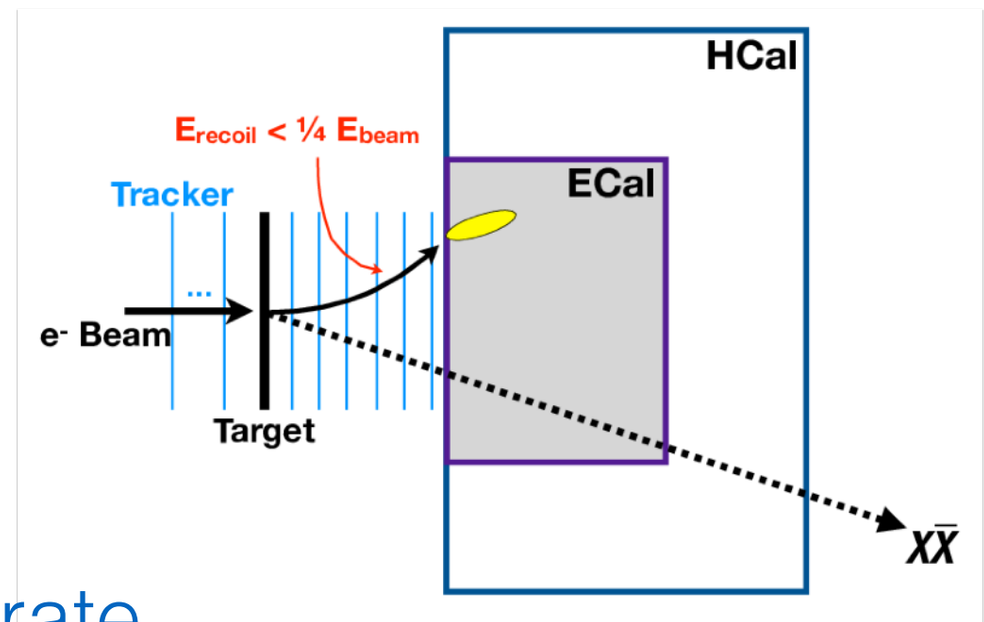
LHCb VELO enables similar idea at LHC, hugging beam

e beam: HPS

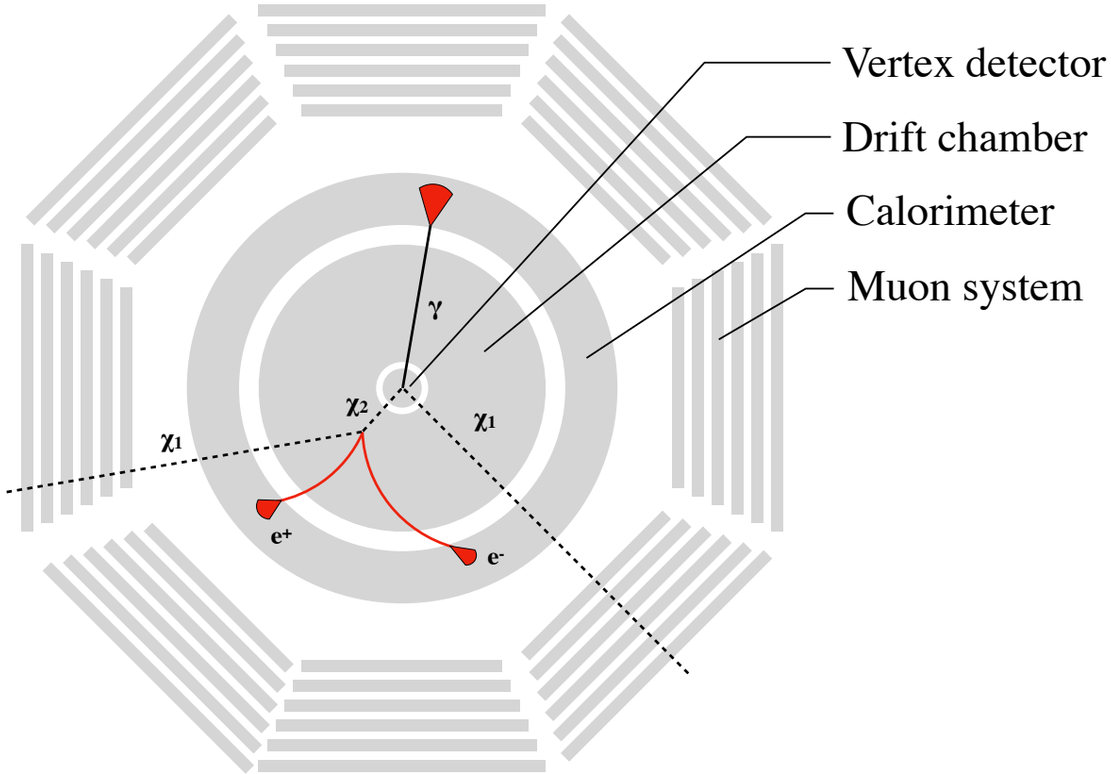
Unique capability to "image" individual beam particles for DM search *a la* NA64, LDMX

rely on low bunch charge

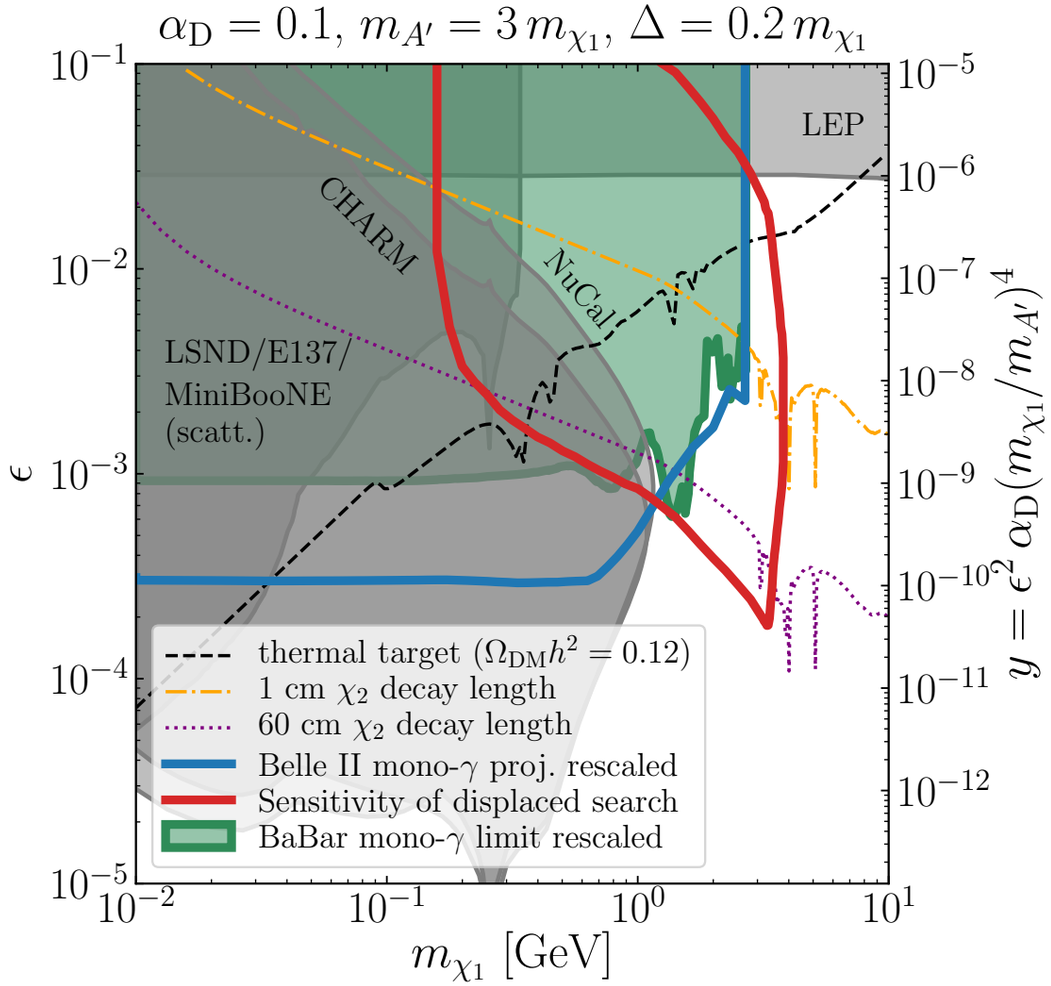
⇒ motivates high repetition rate



Friendlier Environment for Low-Energy Final-States



- Belle-II inelastic DM production search [1911.03176] exploits **O(50 MeV)** energy & pair-mass thresholds



Rest of the RF6 program + plans

We will have 5 short talks on future experimental probes of light dark sectors:

	Padme	*Mauro Raggi* 11:30 - 11:40
	Future PADME runs	*luca Marsicano* 11:45 - 11:55
12:00	**DarkQuest**	*Cristina Ana Mantilla Suarez* 12:00 - 12:10
	LDMX	*Tim Nelson* 12:15 - 12:25
	neutron—dark-neutron oscillation	*Joshua Barrow* 12:30 - 12:40

This is a very small sample of experiments.
For a broader overview: RF6 kickoff meeting, week of August 10 (date still TBD).
Stay tuned!

Also please sign up in our mailing list: SNOWMASS-RPF-06-DARK-SECTOR@fnal.gov
and join our slack channel.

More details at https://snowmass21.org/rare/dark

Contacts: Stefania Gori (sgori@ucsc.edu), Mike Williams (mwill@mit.edu)

Goals for This Talk

- "Why are Dark Sectors a compelling opportunity for the next decade?"

Key stories for RF6 this Snowmass

- "How do **small and multi-purpose** experiments **across different experimental frontiers** confront this landscape?" [IF-centric piece]

- Bridging the GeV-to-TeV Gap:
  "The whole is greater than the sum of its parts"

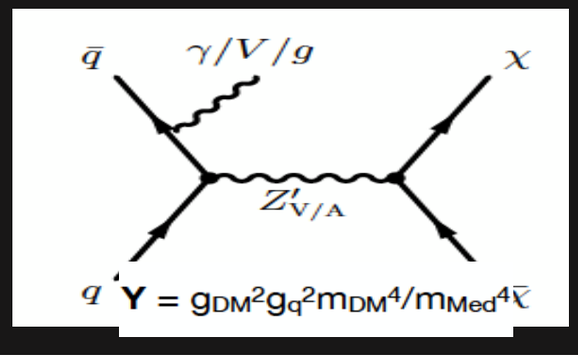
Valuable joint effort for RF6 and EF9,10

Putting it together

Light DM with thermal origin via **Vector Portal**

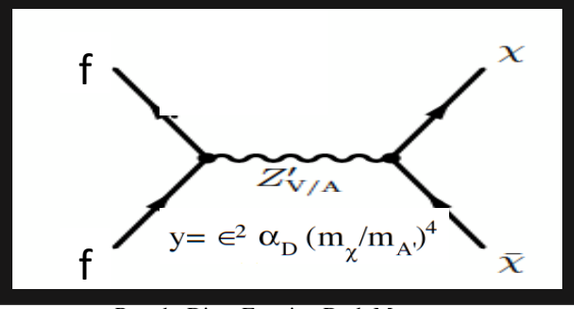
[ATLAS/CMS versus other accelerator-based exps]

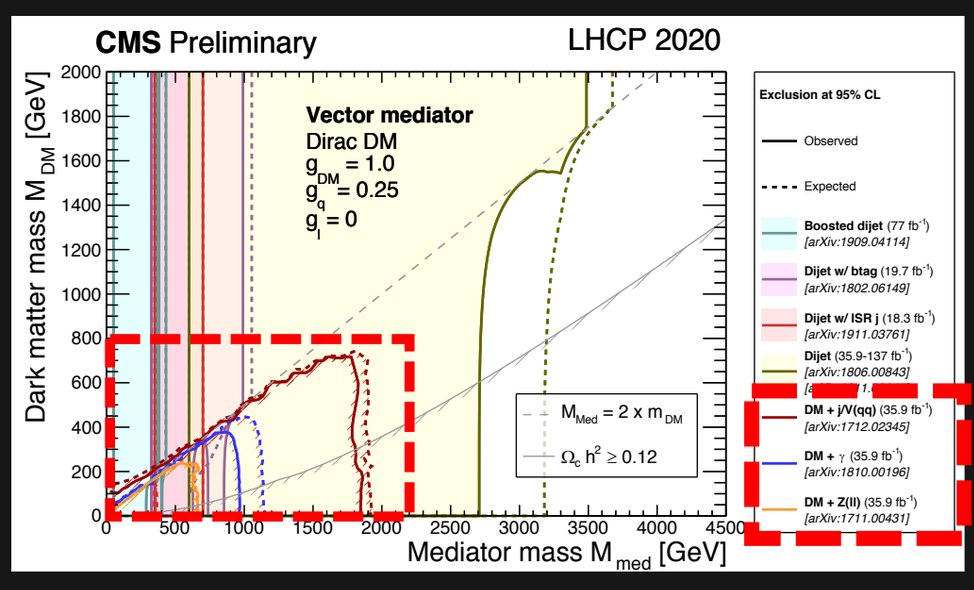
ATLAS/CMS

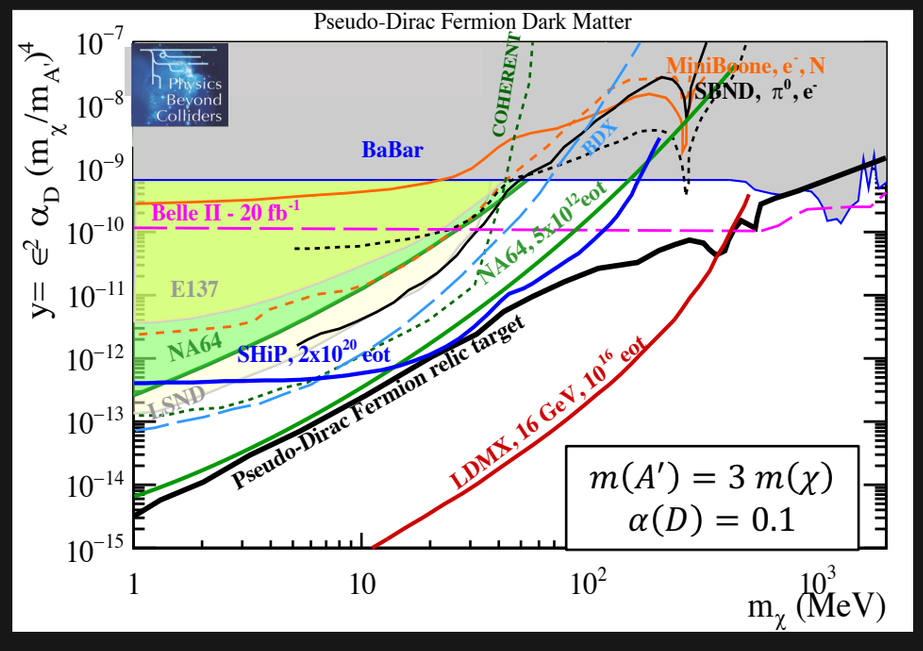


Exactly the same model

Physics Beyond Colliders







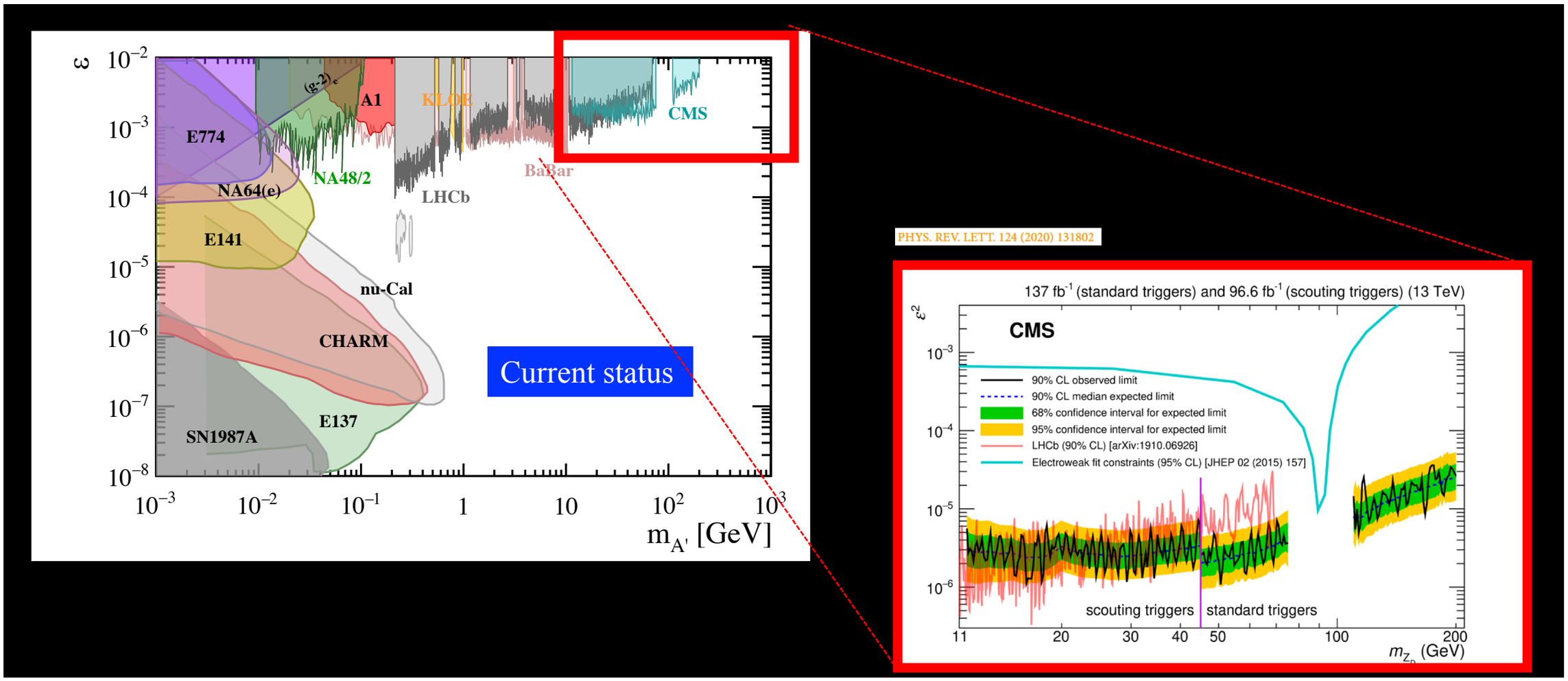
Very different DM mass range (m_{DM}<800 GeV for ATLAS/CMS; m_{DM}< few GeV for PBC);
Still in the same mass range (<10 GeV) we should be able to compare results

24

Gaja Lanfranchi DM@LHC slides

Putting it together

Scouting searches are exploring the gap between prompt light-A′ and heavy-Z′ searches



Gaia Lanfranchi DM@LHC slides

Putting it together

Scouting searches are exploring the gap between prompt light-A′ and heavy-Z′ searches

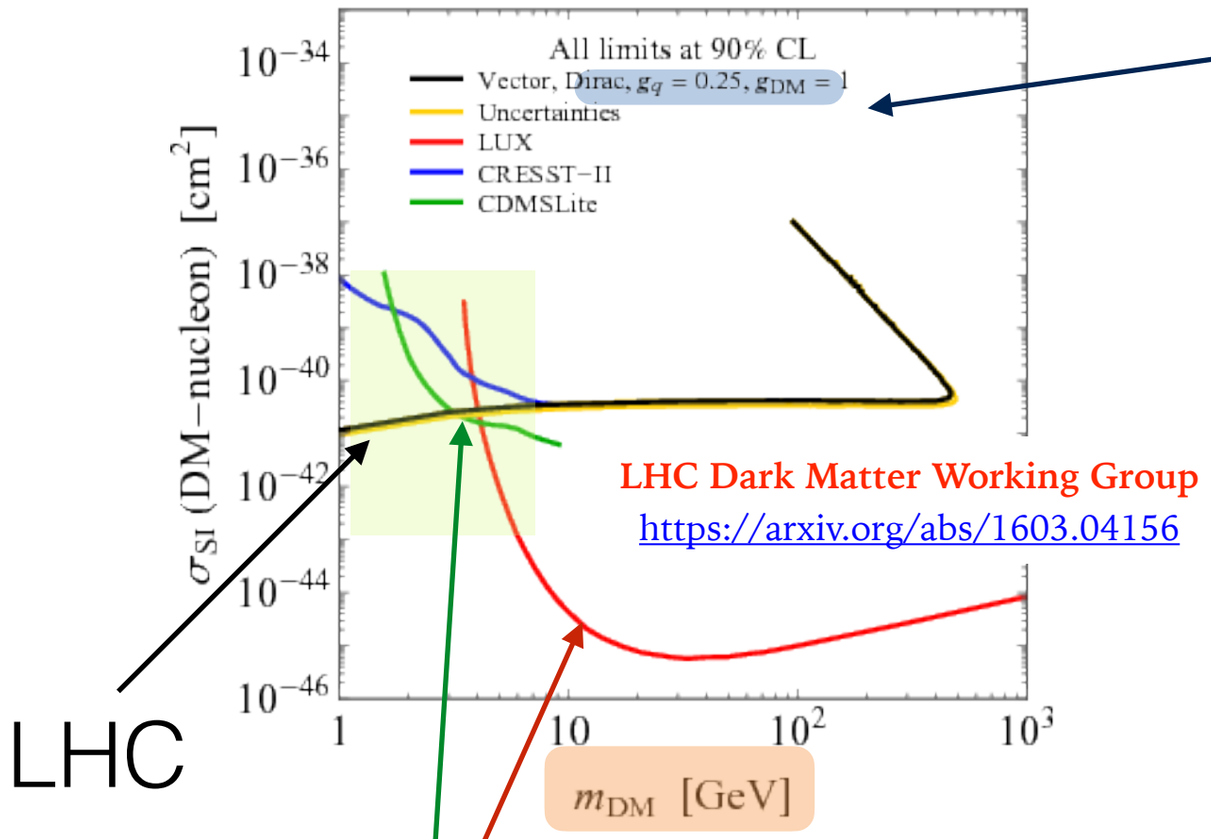
- This is an important story to tell. It crosses working group boundaries in **physics mass scale** as well as **facility**

- There's more to the story:
  - Long-lived searches
  - Scalars
  - Neutral Heavy Leptons
  - **Dark Matter**

In addition to devising own benchmarks, EF and RF groups benefit from identifying common ones!

Putting it together: DM

- ≲10 GeV DM is a range where energy frontier constraints are particularly powerful



...but also contingent on heavy, strongly-coupled mediator

LHC Dark Matter Working Group
https://arxiv.org/abs/1603.04156

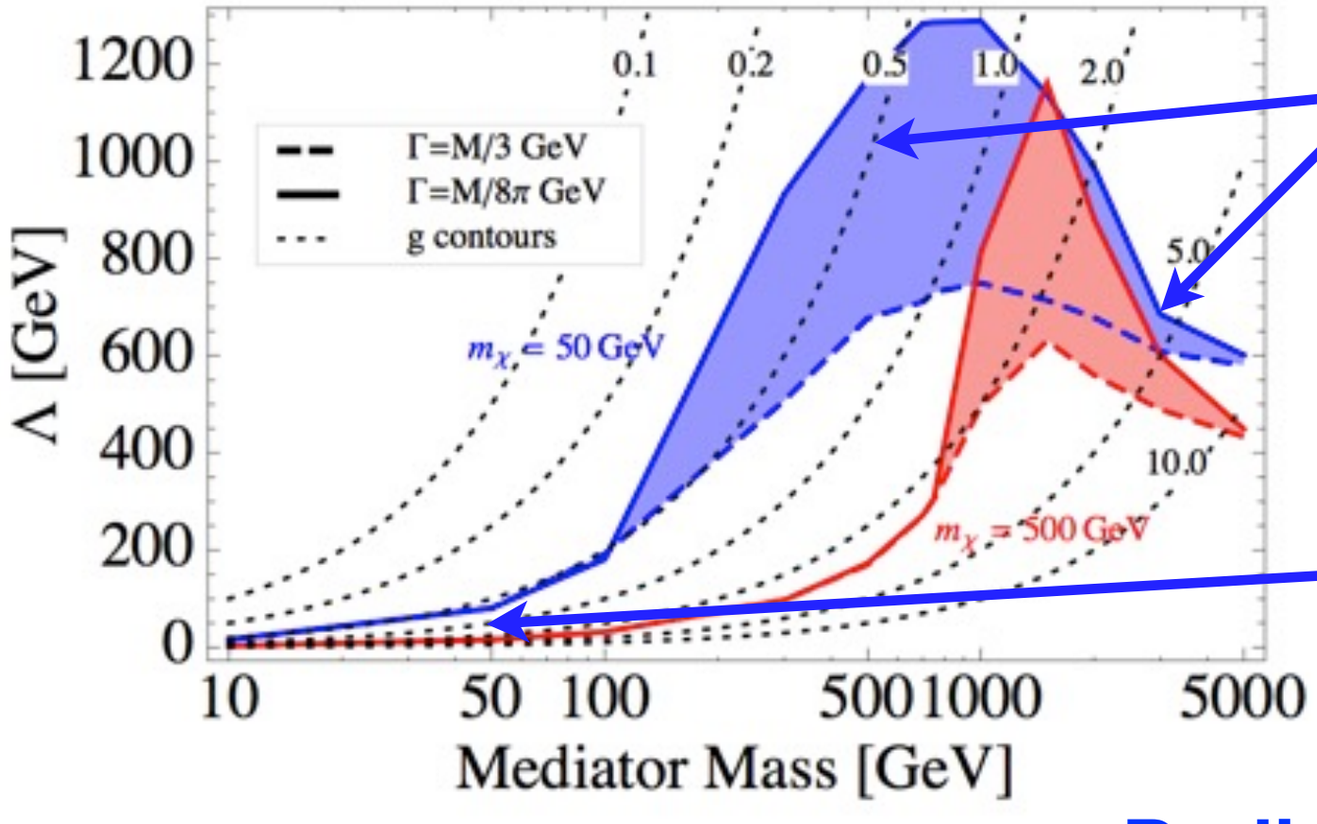
LHC

Direct detection

Putting it together: DM

- ≲10 GeV DM is a range where energy frontier constraints are particularly powerful

[Fox, Harnik, Primulando, Yu 1203.1662]



…but also contingent on heavy, strongly-coupled mediator

Large coupling → DM produced efficiently
High mass → higher MET than background

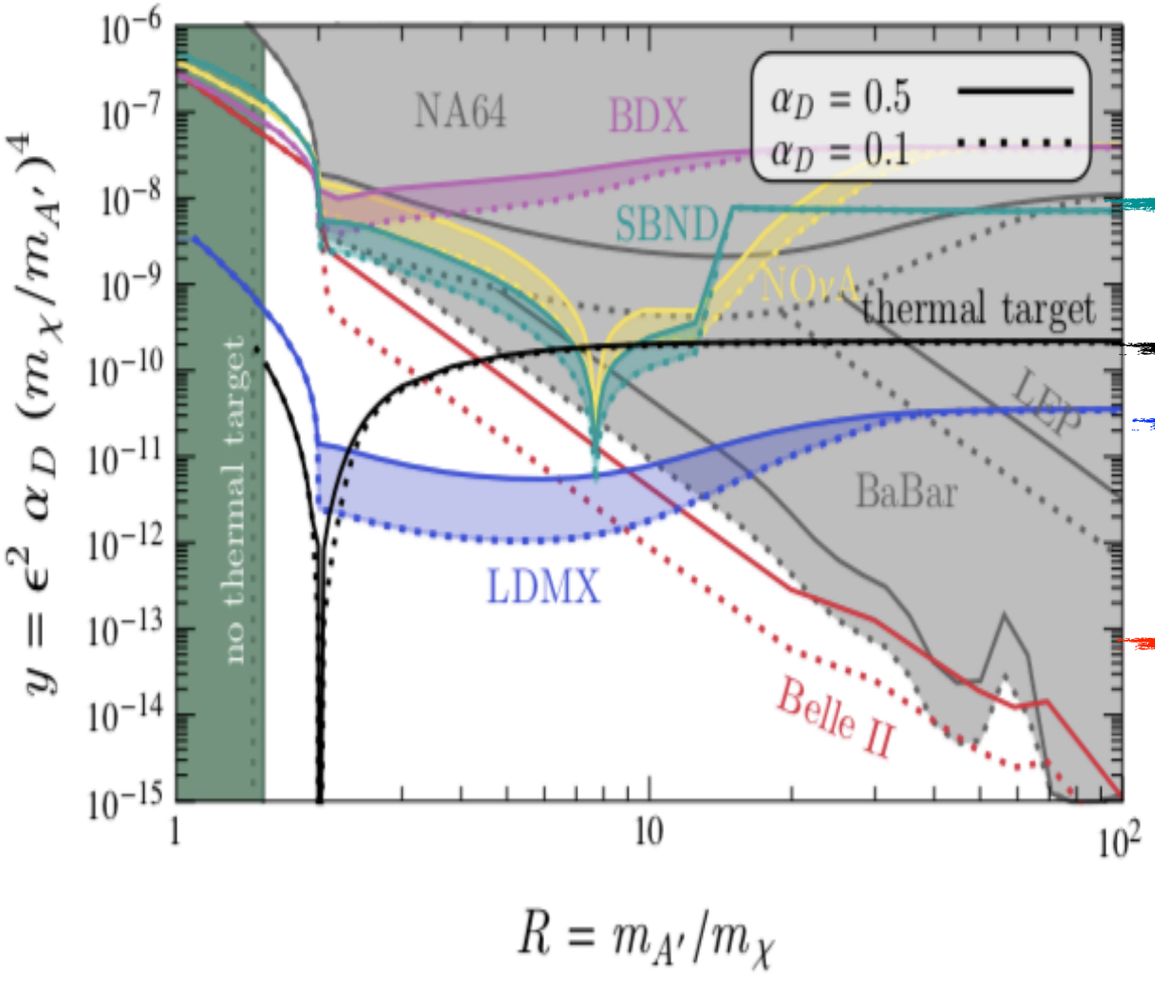
Low DM yield, kinematics is background-like

Note $\sigma_{SI} \sim \Lambda^{-4}$

Dedicated effort towards improved low-coupling sensitivity is ongoing

Putting it together: DM

- Low-energy accelerator-based searches often face complementary criticism that they rely on kinematically accessible mediator. This is not entirely true…



sensitivity to production of DM through inaccessible mediator

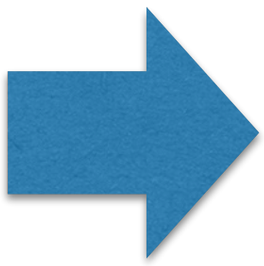
BUT…energy-frontier searches do best for large mediator masses

Plot from 2003.03379

The Whole is Greater than the Sum of its Parts

- When the low- and high-mass focused physics join without gaps, considering both together allows a more powerful, robust scientific conclusion than considering them separately.

- The combination is even more important in the opposite case – **it's hard to fill a gap you don't see**.



we need to figure out combinations

Conclusion

- Dark Sectors represent a broad arena for new physics, with dark matter as powerful motivation; **much is unexplored; bounded, reachable and motivated regions of parameter-space represent exciting directions for near-term experiments.**
- Next steps
  - Expand on the success of the BRN in framing this motivation, broadening scientifically
  - Refine the story of how different types of experiments complement each other in this effort
  - Working with EF9 & 10 to bridge the GeV-to-TeV Gap
  - Continue identifying new opportunities

Rest of the RF6 program + plans

We will have 5 short talks on future experimental probes of light dark sectors:

	Padme	*Mauro Raggi* 11:30 - 11:40
	Future PADME runs	*luca Marsicano* 11:45 - 11:55
12:00	**DarkQuest**	*Cristina Ana Mantilla Suarez* 12:00 - 12:10
	LDMX	*Tim Nelson* 12:15 - 12:25
	neutron—dark-neutron oscillation	*Joshua Barrow* 12:30 - 12:40

This is a very small sample of experiments.
For a broader overview: RF6 kickoff meeting, week of August 10 (date still TBD).
Stay tuned!

Also please sign up in our mailing list: SNOWMASS-RPF-06-DARK-SECTOR@fnal.gov
and join our slack channel.

More details at https://snowmass21.org/rare/dark

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